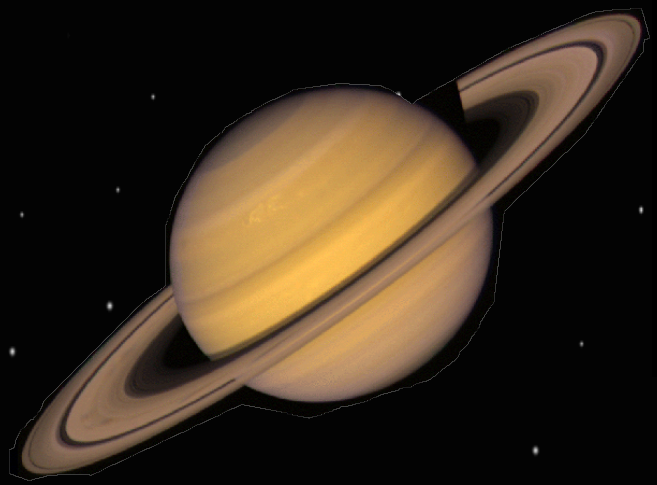
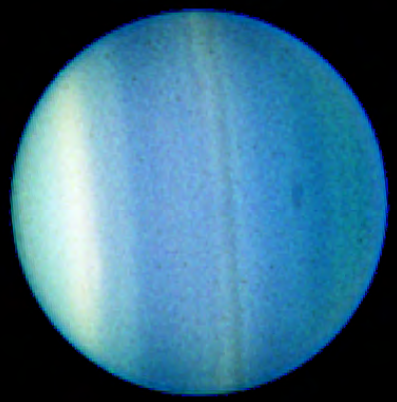
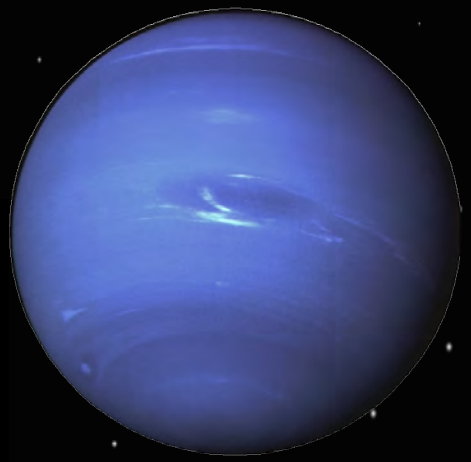
Outer Solar System Exploration







Outer Planets Assessment Group (OPAG) Report to PSS March 2015

OPAG Charter and Meetings

- OPAG regularly evaluates outer solar system exploration goals, objectives, investigations and required measurements on the basis of the widest possible community outreach. The group assembles twice per year to assess the current state of outer solar system exploration, goals for future exploration, and technology development needed to achieve those goals.

- The most recent OPAG meeting was 19-20 February 2015 at NASA Ames

- An OPAG townhall was held at LPSC 18 March

- The next OPAG meeting will be August 24 – 26 at APL

OPAG Overview

- Our challenge has been to bracket the looming gap in missions to the outer solar system, and now to minimize the impact of the gap
- The near-term future for outer solar system exploration is bright
  - Juno at Jupiter
  - Cassini at Saturn
  - New Horizons flyby of Pluto
- After that outer solar system exploration consists of
  - Some participation in JUICE
  - New Horizons flyby of a KBO
  - **A new Europa Mission !!!!!**

What do we need to do to achieve a healthy program of outer solar system exploration

OPAG Findings address the need to:

A. Maintain support for current missions and data analysis
B. Support a new start for a Decadal-Survey-responsive Europa mission *as soon as possible*
C. Invest in power sources appropriate for the outer solar system
D. Make sure that outer solar system missions have a home in Discovery and New Frontiers
E. Go after other opportunities with international collaboration, e.g. ESA's M4; Participating scientists on EXCEED
F. There will be a gap in data for >10 years; how do we maintain a knowledgeable outer solar system community of scientists?
   - Keep that gap as short as possible
   - CDAP extension

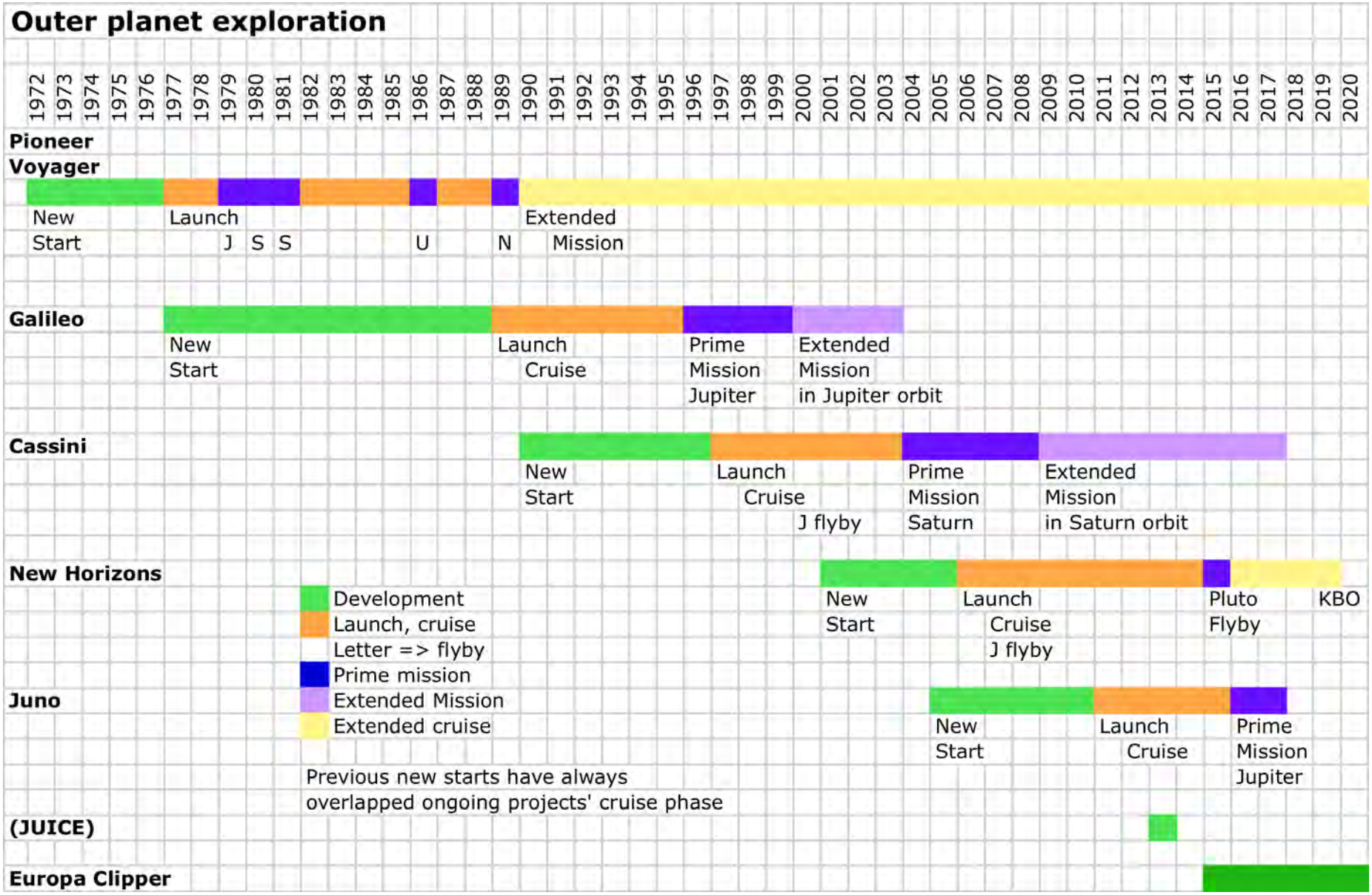
OPAG FINDINGS

From the February 2015 OPAG meeting, modified at the LPSC townhall

1. Get the mission to Europa going

- **Europa** remains the highest priority mission destination for the outer planets community. OPAG lauds in no uncertain terms the inclusion of funding for a new start for a Europa mission in the President's FY2016 budget. A tremendous opportunity presents itself to NASA and the nation. *A properly designed and instrumented mission to Europa will markedly advance our understanding of the Outer Solar System, and may very well revolutionize our understanding of life in the Universe. We continue to strongly support the Europa Clipper as a scientifically compelling, technologically feasible and fiscally responsible approach to exploration of Europa.*

- ***OPAG finding: OPAG strongly encourages NASA to continue work on the Europa Clipper. OPAG wishes to be informed at the earliest opportunity of NASA's plans for Europa mission formulation during phase A, including but not limited to the selection of instruments. Modest expansion of instrumentation to do important plume science, should that opportunity exist at Europa, is encouraged, but only if the budget allows, and not at the expense of the core payload or at the price of a significant delay to the launch.***



Exploration will continue, with the new start of the Europa mission, but there will be a >10 year gap without data return

2. Looking ahead to assessing habitability

- A workshop on possible strategies for detecting life in a Europa plume was held immediately prior to OPAG meeting. Several OPAG Steering Committee members were in attendance. As exciting as this concept is, OPAG urges caution on the part of NASA. As presented at the workshop, and at the Europa Clipper Science Definition Team meeting Advisory Session on Potential Plume Measurements, held in June 2014, new *HST* observations of Europa have yet to confirm the existence of any plumes on Europa. Plumes may exist but be below the detection threshold of present-day observations, or they may be intermittent. But the lack of definitive observations hinders our attempts at plume characterization, much less instrument design for potential biosignature experiments at Europa.

- OPAG notes that, at present, there is no clear scientific consensus on how to best detect living organisms elsewhere in the solar system, short of bringing back a large volume of samples to terrestrial laboratories. In contrast, assessing the prerequisites for habitability (e.g., water, energy, biogenic elements) is feasible with planetary spacecraft, as is searching for the signatures of life as we know it (specific organic chemical attributes, isotopic ratios, i.e., "biomarkers"). Methods for determining compelling biomarkers and instruments and technology for biomarker detection are worthy of further study by NASA.

- ***OPAG finding: The PICASSO and Matisse programs are ideally suited for the technology development required for instruments for the payload of a future "biosignature" missions, anywhere in the solar system.***

3. Maintain Current Mission Support

Focus on Cassini's Legacy

- *Cassini is NASA's premier flagship mission.* Cassini's data return from the Saturn system continues to inspire, challenge and enchant us. Cassini has passed the senior review milestone, and funding is secure for the Grand Finale phase of the mission. Many thanks to NASA HQ for selecting nine additional Cassini Participating scientists in the most recent CDAPS cycle. To date, Cassini Participating Scientist program has incorporated over 30 new participating scientists into the Cassini teams. Looking ahead, we urge NASA to consider continuing CDAP well past Cassini's demise in September 2017. The unique end-of-mission science will take time to analyze, promising new results on the origin and evolution of Saturn, its rings and moons. Once the Cassini mission ends the CDAP program remains the best place to fund continued research on these data. The end of project funding for Cassini PI's, Co-Is, and other science associates will push the entire group into the R&A program to continue their research. We also note that there is considerable pressure to keep science teams small during the mission development phase, which also increases pressure on the R&A program to sustain outer solar system scientists between missions' operational phases.
- ***OPAG finding: The CDAPS program has been incredibly successful in funding analysis and modeling of the wealth of data collected by Cassini. Continuation of CDAP (or possibly OP-DAP [Outer-Planets-DAP]) until the Europa mission is on its way will help to bridge the large gap before the next outer solar system mission and ensure that a knowledgeable cadre of outer planet scientists will be ready to operate and analyze data from the Europa mission instruments.***

4. New Frontiers

- **New Frontiers -** OPAG welcomes and strongly supports the news of $5 million for a New Frontiers mission start. Beginning a New Frontiers mission at this time is directly in line with recommendations in the Decadal Survey that NASA select two New Frontiers missions in the decade 2013-2022. These medium-class, directed missions at a complete cost of close to $1 billion allow the NASA planetary science community to target regions of great importance in the solar system with capable missions of moderate breadth. These missions especially enable outer solar system science, as four of the seven proposed New Frontiers destinations could be outer solar system targets. Insertion of a New Frontiers mission amid a Discovery selection and the new start of a Europa flagship mission enables us to achieve major Decadal Survey goals, engage the planetary science community and maximize science return per dollar.

- ***OPAG finding: OPAG recognizes the funding challenges PSD has faced for the past few years. Thus, we are especially appreciative of, and register our support for, the New Frontiers program, and are pleased that the administration has requested funds to restore this critical program.***

5. A home for outer solar system missions in the Discovery Program

- OPAG supports a robust and continued Discovery Program that welcomes a diverse set of missions, including those to outer solar system targets. We applaud recent changes to the Discovery Program (removal of Phase E costs from the cap) that remove a significant competitive cost disadvantage for proposed missions to the outer planets, which require longer duration transits. OPAG recognizes that some outer planets missions are only possible with radioactive power sources and recommends that NASA HQ include RPS as GFE within the Discovery Program.

- ***OPAG finding: OPAG strongly endorses removal of phase E costs from the Discovery cap, and recommends inclusion of RPS as GFE within the Discovery Program.***

Outer Solar System Challenges

- ***Travel time*** – OPAG is intrigued by the potential for use of the SLS, which could considerably shorten the time required to get to outer solar system destinations, or substantially increase the mass available; however a cost model must be developed that fits within normal PSD expenditures for launch vehicles
- ***Power*** – solar power has now been shown to be viable as far out as Jupiter, but with current technology to go beyond Jupiter (or to places with inherently little sunlight such as polar regions) Radio-isotope Power Systems (RPS) are still required. Getting domestic production of Pu238 restarted was an important milestone reached last year.
  - Near-term there must be a focus on getting all the steps in the RTG production line working to fuel the current generation of RTGs
  - OPAG supports important technology developments are underway for the next generation of RTGs
  - There are no current outer solar system mission concepts that require development of fission power

6. Invest in power sources needed for outer solar system exploration

- There are many potential planetary missions that require use of Radio-isotope Power Systems (RPS), including all that would venture beyond Jupiter. OPAG has a keen interest in RPS because that is currently the only viable option for power for ice giant missions. To build on the demonstrated reliability of MMRTG technology (and therefore mission success), increase efficiency of Pu238 usage, and boost end-of-life mission power, the OPAG advocates the Planetary Science Division's continuous upgrade development path for radioisotope thermoelectric generators and Stirling generators.
- ***OPAG finding: The re-start of domestic production of Pu238 is a significant achievement and enables our continued exploration of the outer solar system. It is important to continue to invest in future technologies thus OPAG also endorses PSD's evaluation of other potential nuclear power system developments (the Nuclear Power Assessment Study) to meet future mission needs, and would like that study report to be released as soon as practical.***

7. Research & Analysis programs

- R&A is an essential part of maximizing science return from NASA's missions, and was recognized by the Decadal Survey as an essential part of a balanced program of planetary exploration. OPAG is naturally concerned about the low selection rate in recent years for the OPR and CDAPS programs especially. Because the looming decade-long gap in outer solar system missions means that many scientists with that expertise will have to be funded largely or even purely through R&A, we are concerned that we will lose vital skills and knowledge as many outer solar system scientists may be forced to leave the field or seek alternative subjects of study.

- The reductions in the PSD budget over the past few years have stressed all elements of NASA's planetary exploration effort. We may have turned a corner, however, with the new start for Mars 2020, a projected new start for the return to Europa, a restart of Pu-238 production, a new Discovery proposal round underway, and concrete plans for the next New Frontiers call. Overall R&A funding has been essentially flat the last few years. It is time to consider increasing this element of the planetary portfolio, to bring it in line with the rest, and maximize our nation's return on its investment.

7. Research & Analysis programs (cont.)

- In addition, the time dedicated to R&A discussion during OPAG meetings continues to grow. It is clear that our community has many questions about, for example, how SSW with two Step-2 deadlines is being implemented, programmatic balance within the new R&A programs, and the distribution of funding between programs. OPAG believes clarity regarding the new R&A organization would go along way toward addressing community concerns. Although some data is currently available on the SARA site, R&A funding is distributed between multiple lines and remains difficult to track.

- ***OPAG finding: OPAG finds that increased funding to the R&A programs would improve selection rates and allow more excellent peer-reviewed planetary science and data analysis to proceed. In order not to lose vital expertise in outer solar system science in particular, we encourage NASA to implement a funding line specifically for the outer solar system, similar to MDAP, that would include analysis of data from recent and current missions and planning for future outer planets missions, including JUICE, Europa Clipper, and Cassini. Finally, better communication is key to building confidence in the restructured R&A program. We suggest that quarterly townhall meetings (some could be online) be held to enable productive communication between the science community and program managers.***

8a. International Collaboration: ESA's M4 Cosmic Vision

- **US Participation in ESA's M4 Cosmic Vision**. As numerous projects have demonstrated, strong, close international collaboration greatly increases mission capabilities and resources, enhancing scientific achievements. In many cases, international collaboration is an enabling factor for missions. OPAG lauds NASA[1]s support of several responses to ESA's M4 Cosmic Vision call.

- ***OPAG finding: The collaborative international partnerships built by missions such as Cassini-Huygens represent decades of effort and investment, and benefit science immensely. In addition to support of the current M4 call, we encourage NASA to look ahead to identify opportunities and find mechanisms to enable collaboration on projects of high priority to both NASA and ESA that would otherwise be out of reach for either agency alone.***

8b. International Collaboration: EXCEED Participating Scientists

- EXCEED is a UV telescope on board the JAXA mission Hisaki in orbit around Earth. Its primary objective is to observe the Io Plasma Torus and Jovian aurora.

- ***OPAG finding: OPAG recommends that NASA-SMD add a Participating scientist program call within a ROSES 2015 amendment to facilitate the further involvement of US scientists in the EXCEED investigation on the JAXA Hisaki mission. The results obtained will support ongoing Juno, MAVEN, and HST programs within the program period and will better inform the plans for future Europa Mission and JUICE investigations. NASA's support would provide additional rationale for extending Hisaki's science mission beyond 2017.***

9. Earth-based observations for missions

- Earth-based, telescopic observations of planetary objects being studied by spacecraft enable greater science return than the mission itself can provide by giving context to the spacecraft data, and by observing the object for a longer time or with different instruments. The Galileo, Cassini, and New Horizons missions have already benefitted from earth-based observations that yielded contextual information on Io's volcanoes and Jupiter's clouds, for example. Future Juno-related science in particular can benefit from use of ground-based assets to find hotspots and to predict the location of major atmospheric features to facilitate targeting of Juno's JunoCam and JIRAM instruments.
- Some of the key elements for such support are non-US assets. A previous example of such support was the use of the National Astronomical Observatory of Japan's Subaru Telescope for New Horizons. Such support could easily reflect the interests of their own space scientists and astronomers. For example, ground-based support by the Subaru Telescope would provide complementary information to the Juno campaign suggested by Astro H / investigators that, in turn, supports Juno mission science. Ground-based support by ESO's Very Large Telescope would also provide direct support for European scientific interests on Juno, e.g. the Italian-led JIRAM investigation.

- ***OPAG finding: OPAG encourages NASA to support earth-based observations in general that leverage greater science return from active missions, including non-US assets. We urge NASA to contact key personnel in the appropriate agencies to arrange for such support as early as possible.***

10. Early Career Researchers

- Early career researchers represent the next generation of planetary scientists. Early career scientists (ECS) face unique pressures with regards to establishing themselves, acquiring practical experience, and funding their research. Even the most successful members of the ECS community are concerned about their ability to stay in science.

- Mission teams have historically been comprised of established scientists with a few early career participants. Fewer active missions provide fewer opportunities for early career scientists to learn and gain experience from their more senior colleagues. Current trends in mission proposal announcements have brought downward pressure on Phase E budgets, shrinkage of science teams, and an emphasis on minimizing science team size and support throughout development. This is at odds with NASA's need to train early career scientists for the jobs that await in the decades to follow. With a gap in outer planets missions looming, and proposal pressure increasing, outer planets ECS are especially at risk of falling through the cracks, compromising NASA's ability to staff the next generation of planetary science missions with experienced leadership.

- ***OPAG finding: OPAG encourages NASA to continue funding Early Career Fellowships and to consider ways to increase participation of ECS in planetary missions, from Phase A-D through Phase E. OPAG encourages NASA to continue monitoring the involvement of ECS in planetary missions as well as the R&A program and to find ways to maintain the experienced ECS population needed to conduct future missions.***

OTHER OPAG BUSINESS

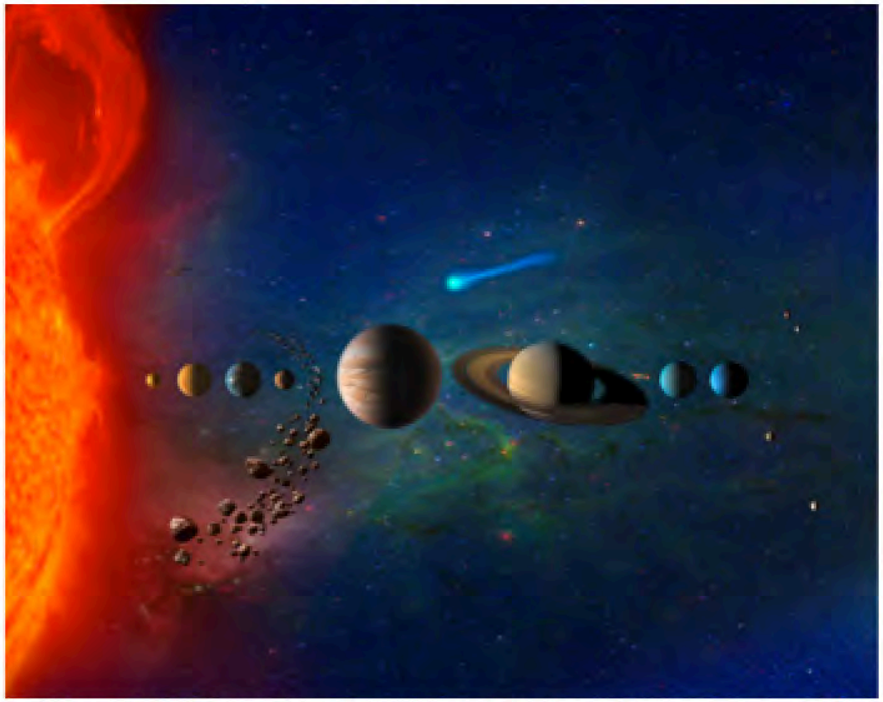
NEW SCIENCE GOALS DOCUMENT

New OPAG Science Goals Document

Posted on the OPAG website:
http://www.lpi.usra.edu/opag/

Scientific Goals for Exploration of the Outer Solar System

Explore Diverse Worlds



How did the outer planets mold the solar system and create habitable worlds?

OPAG Report
DRAFT
6 March 2015

Science Goals articulated by OPAG

- Last full document was in 2006
  - "Scientific Goals and Pathways for Exploration of the Outer Solar System": A Report of the Outer Planets Assessment Group (OPAG) 2006
  - Plus the Decadal Survey white paper 2009
  - Plus the Technology Recommendations 2009

- Vision & Voyages is written and that effort is complete

- Going forward, we decided it was time to update the OPAG Scientific Goals and Pathways report

- Following that we will update the technology plan

OPAG's New Science Goals Document

Motivation

The "Vision and Voyages" writers are done – ***OPAG is the voice of the outer planets community until the next decadal survey*** *– this needs to be a living document*

- React to *new discoveries*
- Focus on *science* rather than missions
- Identify *questions* that can be addressed with New Frontiers and Discovery size missions
    - Like Juno – Juno addresses an important set of questions identified in the 2003 decadal survey with a mission approach completely unlike the mission described in the 2003 DS

- *Prepare* for the next decadal survey
  - What to do about our target-rich blessing/dilemma?

New OPAG Science Goals Document
Approach

- Identify broad scientific goals (start with science, not missions)
- Currently target-body-based, but we'll compare and contrast, and place within context of our over-arching science theme
- (Draft) Over-arching theme: ***How did the outer planets mold the solar system and create habitable worlds?***
- *Want to get to the point that we specify a science question,* then *say what destination addresses that question*
- Starting to craft a multi-decadal vision – what's next after Europa? Why?

New OPAG Science Goals Document

Status

- Initial draft was written by the OPAG Steering Committee
  - Organized by targets
  - Top 5 – 6 goals, not a lengthy laundry list

- The community has given us feedback and provided more content
  - Draft is posted on the OPAG website

- Now we are composing unifying over-arching science objectives; Draft threads:
  - Origin and evolution of the solar system
  - Habitability of icy worlds

- This was a major topic at the February 2015 OPAG meeting
  - Invited 5 "luminaries" in our field to talk about future science goals (Jeff Cuzzi, Toby Owen, Torrence Johnson, Chris McKay, Scott Gaudi)

OPAG: Outer Solar System Vision

Draft threads

- Study origin and evolution of our solar system
  - With major complementarity with exoplanets
- Investigate habitability of icy worlds
  - To gain insight into the origin of life on earth
- Understand the dynamic nature of processes in our solar system
  - importance of time domain

What's next? Baby steps toward implementation; strategic multi-decadal plan

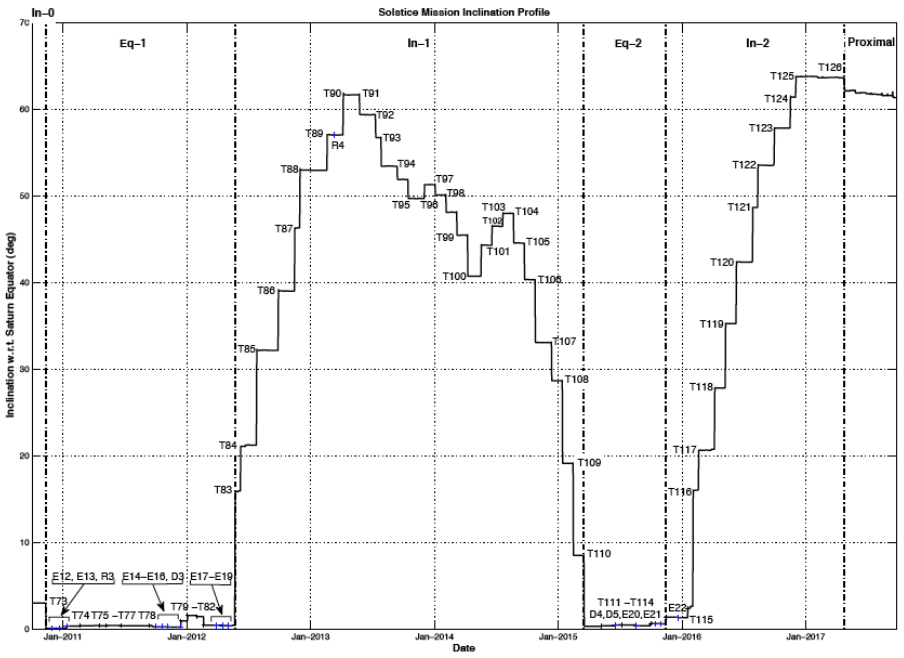
Embrace diversity – explore dynamic worlds

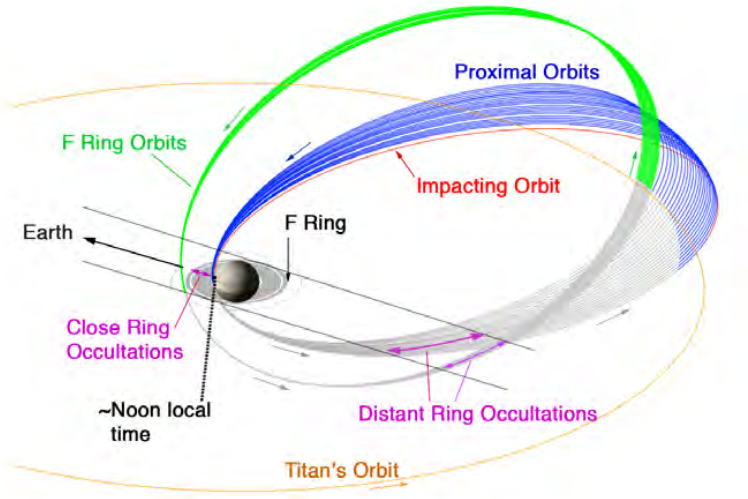
How do the giant planets mold the solar system and create habitable worlds?

UPCOMING EVENTS

The Grand Finale of the Cassini Mission

- Cassini is starting its Eq-2 phase, the last time the orbit inclination will be in Saturn's equatorial plane
- After that the inclination will be pumped up to begin the F ring orbits, followed by the Proximal orbits that plunge between the top of Saturn's atmosphere and the inner edge of the D ring

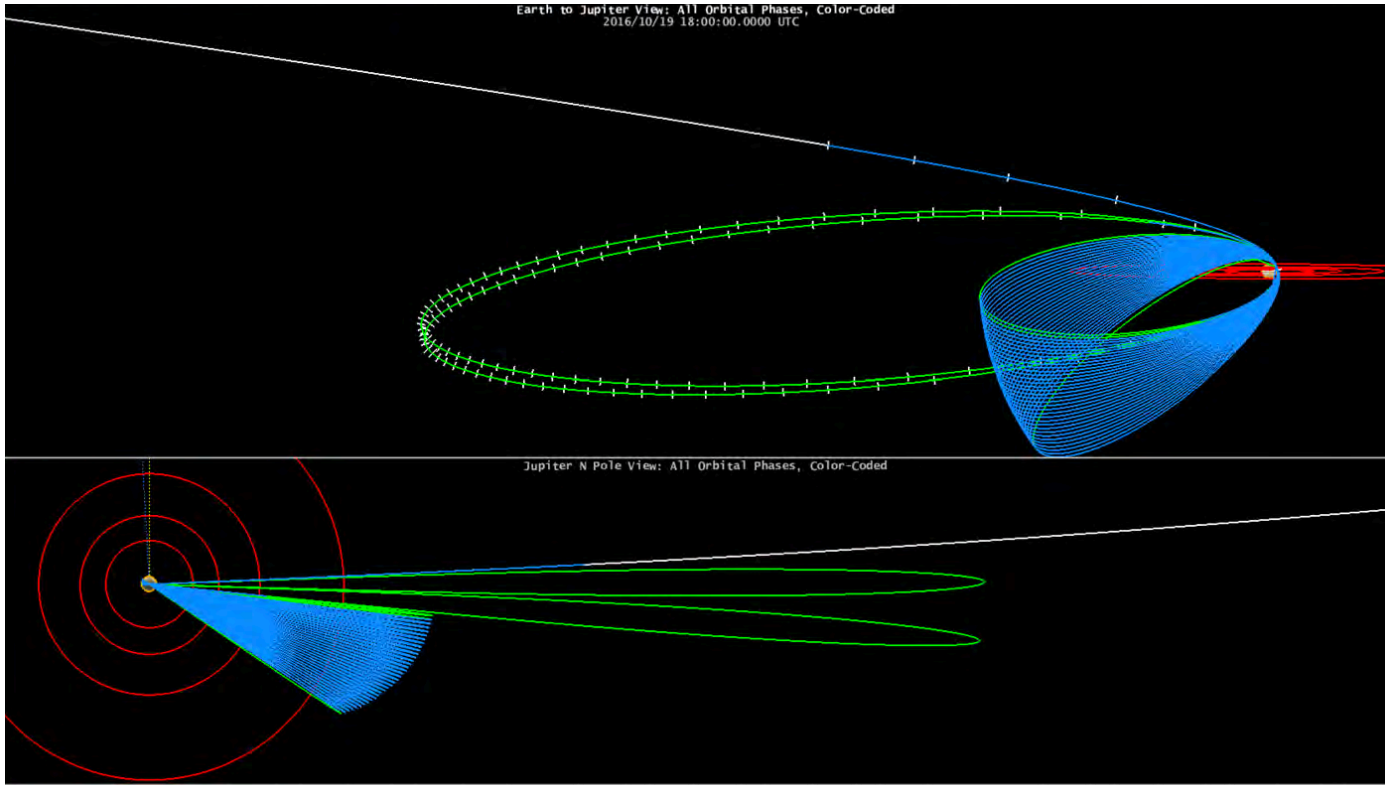




- After a long successful mission at Saturn the Cassini End-of-Mission is planned for Sept. 2017 when the spacecraft runs out of fuel and spirals into Saturn's atmosphere

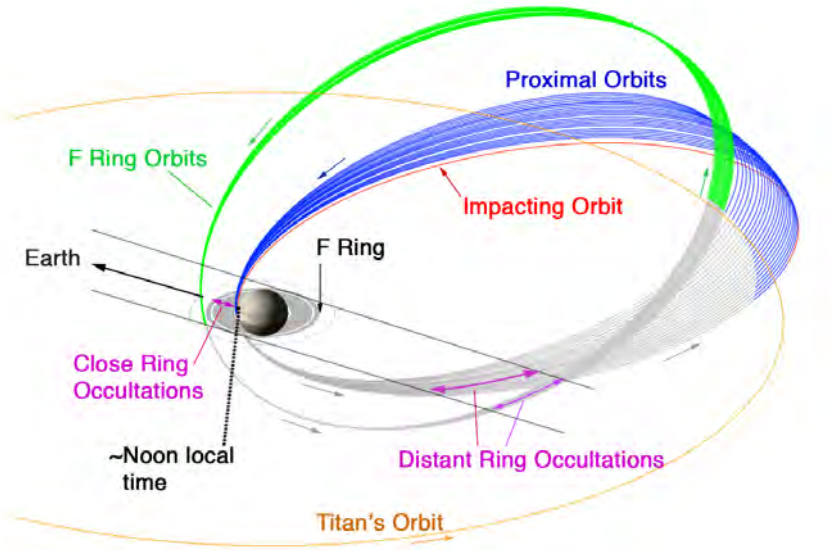
Juno Mission Update

- The Juno project recently made two important changes to its mission plan:
  - The 107 day capture orbit has been replaced by two 53.5 day orbits, allowing the first perijove after orbit insertion to be dedicated to characterization of the environment and observations needed for optimization of instrument configurations for the prime mission
  - The prime mission orbits' period will be 14 days rather than 11 days

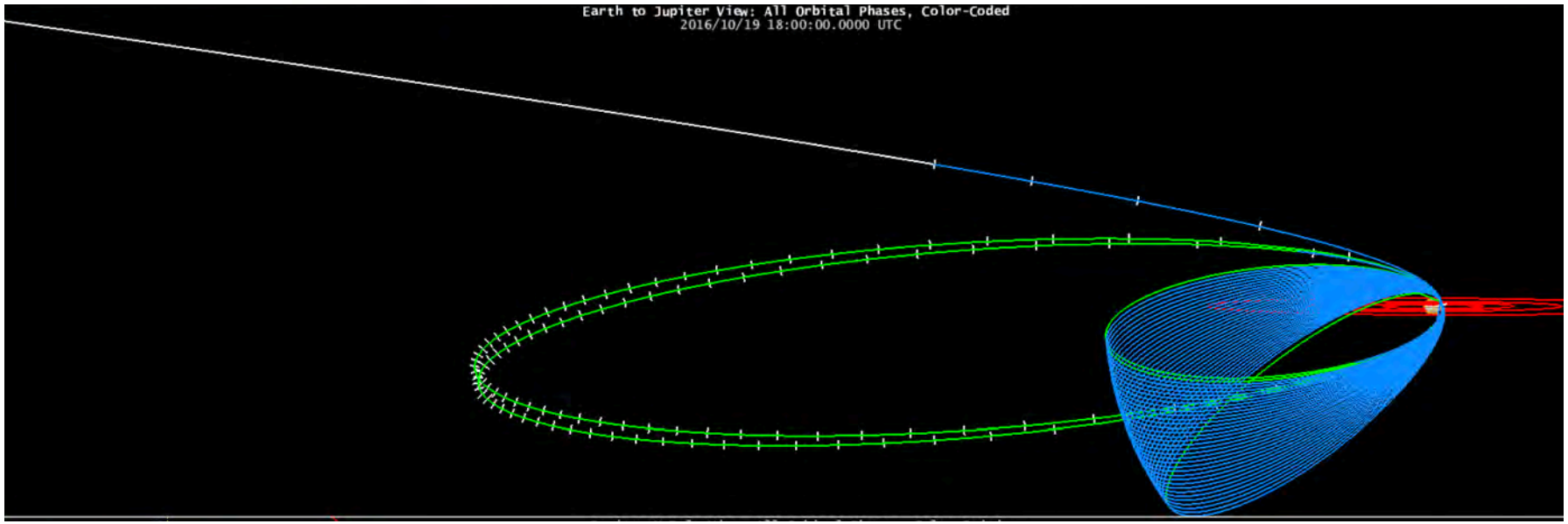


Juno Jupiter Orbit Insertion will take place July 4, 2016

Juno and the final stages of the Cassini mission



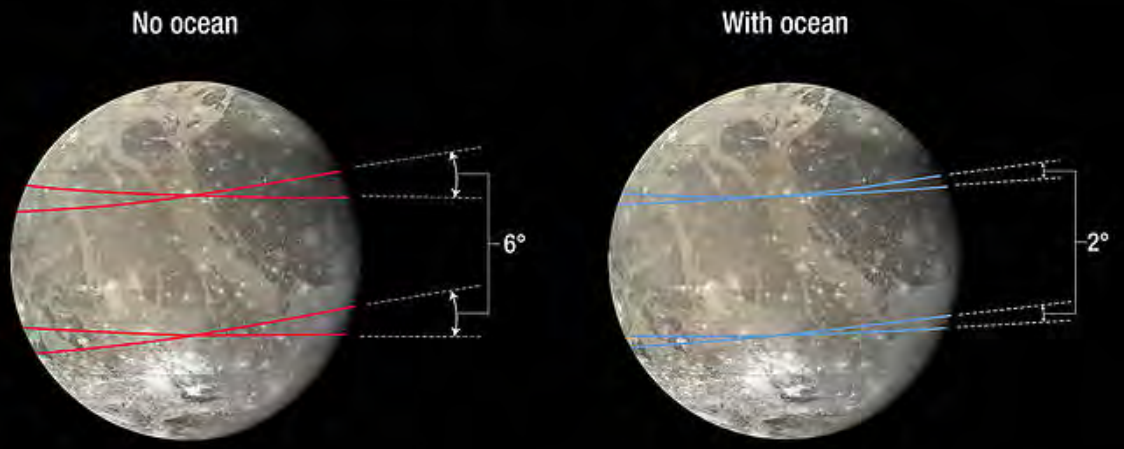
- Similar orbits offer comparable science objectives – giant planet interior structure, gravity field, auroral studies, magnetospheric physics



SCIENCE NUGGETS

Restricted Auroral Oscillation Implies Conductive (Salty) Ocean Deep in Ganymede's Icy Shell

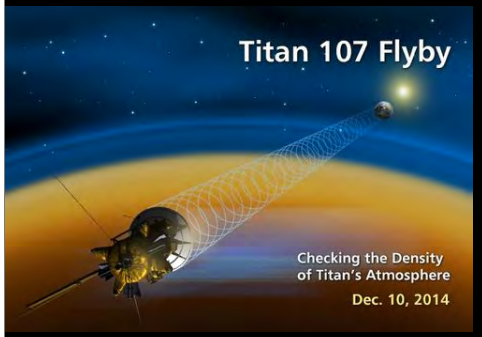
Innovative use of archival HST data



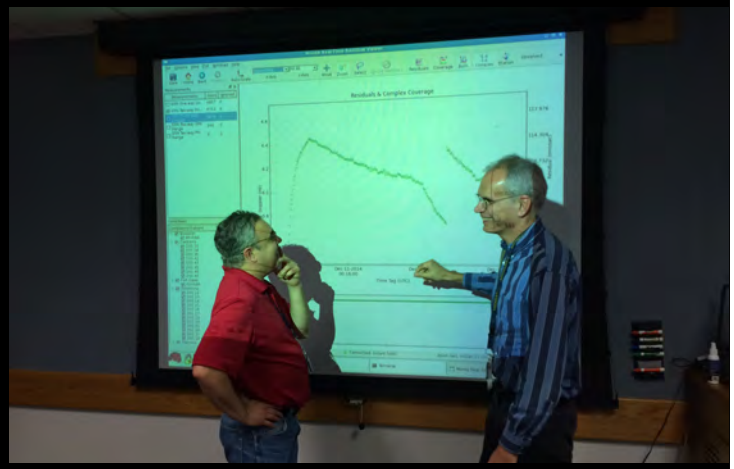
J. Saur et al., JGR Space Physics, 2015

1) Ocean suspected on theoretical grounds
2) Consistent with *Galileo* magnetometer data
3) Can be confirmed by JUICE (and maybe librations)

Three Ways of Measuring Titan's Atmosphere (For the Price of One Flyby)

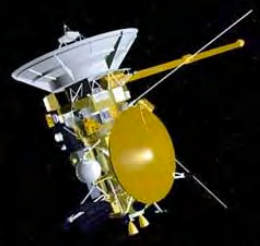


- How dense is Titan's atmosphere? Cassini has three ways to find out
- Important to fully understand Titan's atmospheric structure and and how it changes over time
- T107 is the last flyby where all three methods are used simultaneously



- The Ion and Neutral Mass Spectrometer directly samples atmospheric density

- The Navigation team tracks Cassini's radio signal and determines the atmospheric drag



- The Attitude and Articulation System uses accelerometer and thruster telemetry to estimate drag

Note that any data presented here are unpublished, minimally processed, and undergoing refinement and analysis

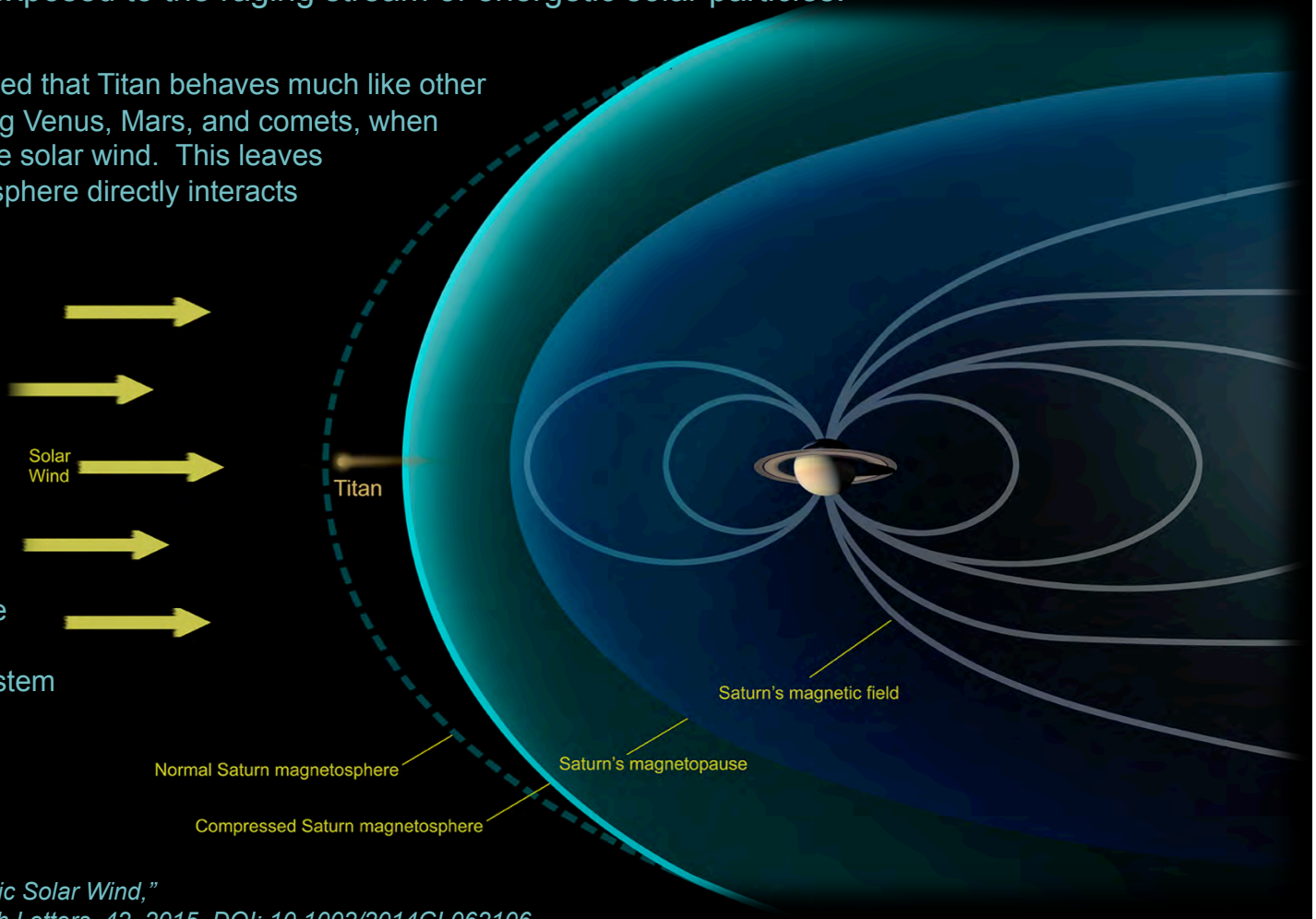
Cassini Catches Titan Naked in the Solar Wind

Titan is nearly always within Saturn's magnetosphere, the vast bubble created by the giant planet's magnetic field. Cassini caught Titan outside that protective magnetic bubble during a flyby on December 1, 2013. A strong surge in solar activity had blown back the sun-facing side of Saturn's magnetosphere, leaving the un-magnetized body of Titan exposed to the raging stream of energetic solar particles.

Cassini scientists have concluded that Titan behaves much like other un-magnetized bodies, including Venus, Mars, and comets, when exposed to the raw power of the solar wind. This leaves Titan unprotected and its atmosphere directly interacts with the undiluted solar wind.

This is not the case at Earth, where the powerful magnetic field acts as a first line of defense against the solar wind, helping to protect our atmosphere from being stripped away.

The finding adds significantly to our understanding of how the sun interacts with magnetized versus un-magnetized solar system bodies.



"Titan's Interaction with the Supersonic Solar Wind,"
Bertucci, et al., Geophysical Research Letters, 42, 2015, DOI: 10.1002/2014GL062106

Measuring the Depth of an Alien Sea

For the first time, scientists have plumbed the depths of a sea on another body in the solar system.

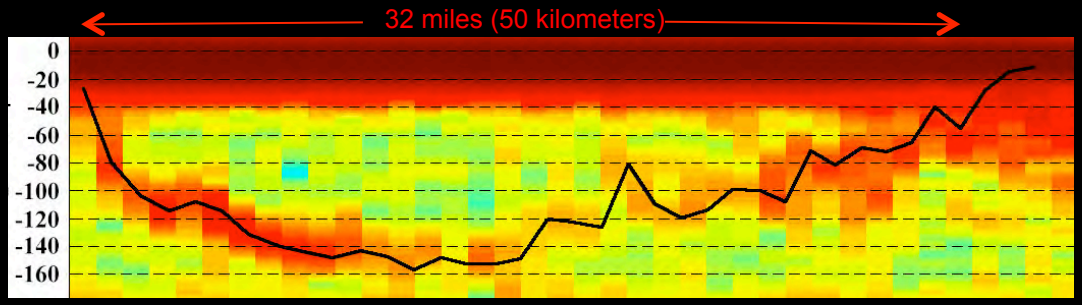
•On Saturn's moon, Titan, Cassini's radar obtained bathymetric (lake depth) measurements of Ligeia Mare, a sea larger than Lake Superior.

•The observation revealed that Ligeia Mare is up to about 560 feet (170 meters) deep and exceptionally transparent to radar. Normally, the radar maps surface characteristics. Its new use for bathymetry has opened the way for similar measurements of other Titan seas by Cassini.

•The measurement was possible because the methane-ethane lake is very pure, which allowed the radar signal to easily pass through, bounce off the seafloor and return to the radar instrument on Cassini.

•Analysis indicates that this liquid, somewhat similar to liquid natural gas on Earth, exists in Ligeia Mare at quantities about 40 times greater than the proven oil reserves on Earth.

Cassini successfully measured the bathymetry (lake depth) of this 50-kilometer track (red lines) across Titan's Ligeia Mare. Latitude and longitude lines from a larger map appear in white.



Colors of each point in the graph show the strength of the radar's return signal, red being the strongest. The position of each point indicates the timing of the signal's return, which corresponds to depth (indicated in meters at left). Top layers of the lake reflected much of the signal (as seen by the deep red at top), while remaining radar pulses passed through and returned off the seafloor.

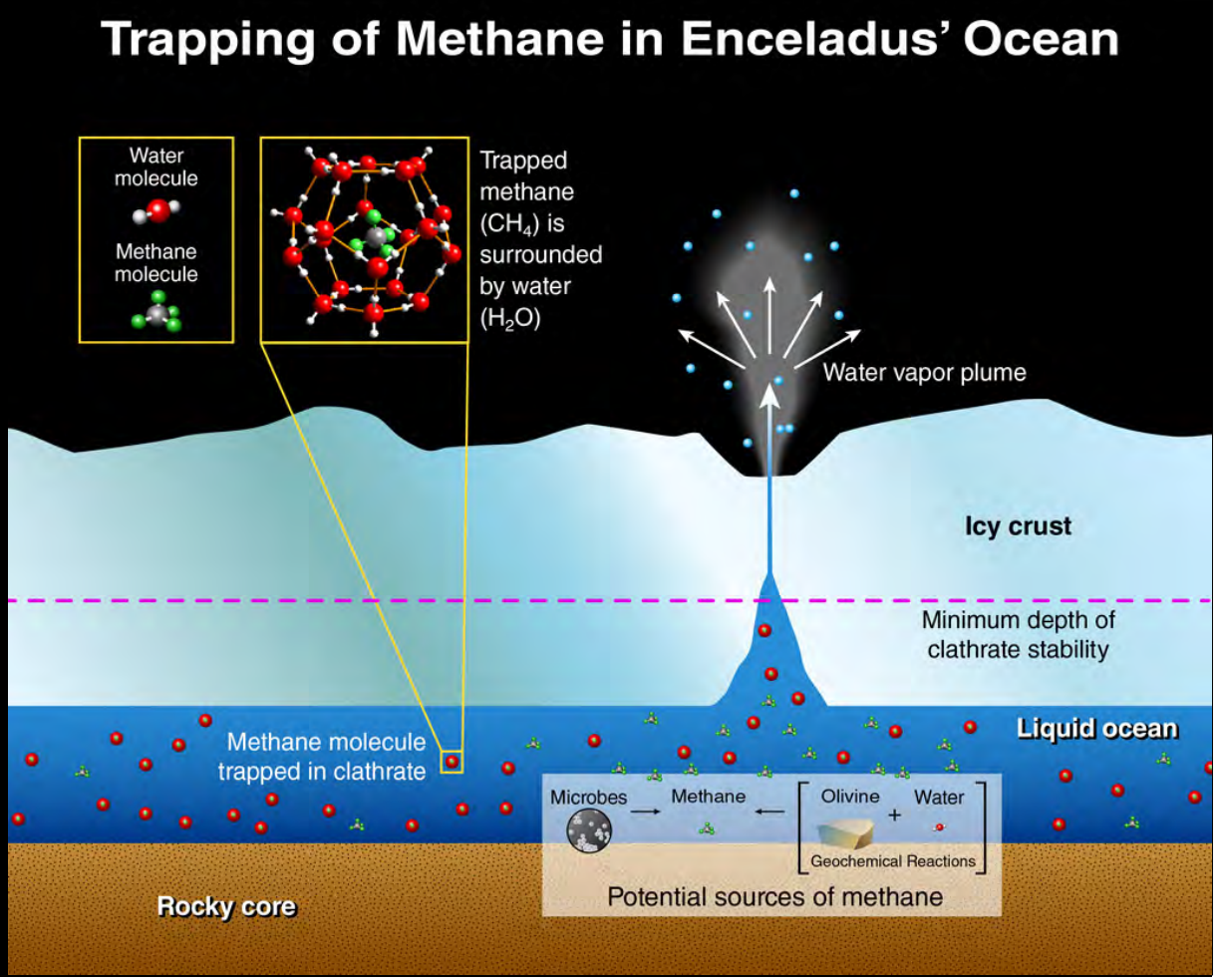
"The Bathymetry of a Titan Sea", M. Mastrogiuseppe, et al., Geophysical Research Letters,41, 1432-1437, 2014.

Methane in Enceladus Geysers Likely Originates from Seafloor Vents

Cassini has found the first evidence of active seafloor hydrothermal vents, where seawater and the rocky core meet to form warm mineral-laden liquid, on Saturn's moon Enceladus. This new finding provides additional evidence for Enceladus' ocean as a possible habitat for life.

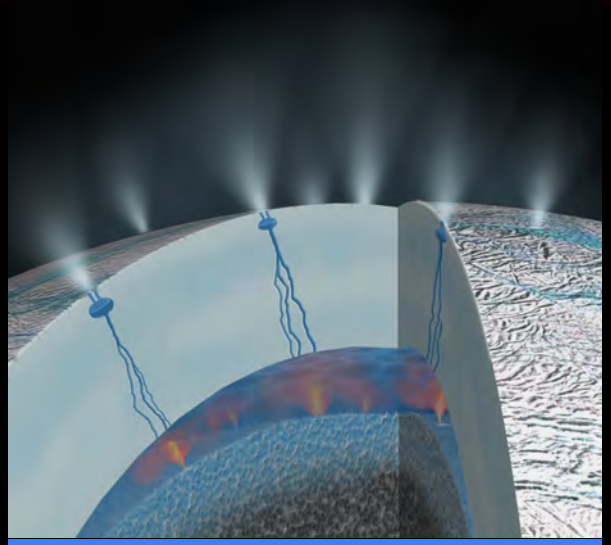
- Cassini's mass spectrometer found abundant methane in Enceladus' vapor plumes. Those plumes are thought to originate within the moon's internal ocean.
- Ocean models show that methane molecules are trapped in ice "cages", called clathrates. So methane should *not* be abundant in the plumes – unless some source is rapidly adding methane in the ocean, faster than it is trapped into clathrates.
- Chemical reactions near warm hydrothermal vents are the most likely candidate for producing additional methane.

"Possible evidence for a methane source in Enceladus' ocean ," Bouquet *et al., Geophysical Research Letters,* March 12, 2015.



Telltale Geyser Dust from Enceladus Seafloor Vents

Cassini discovers the first evidence for ongoing seafloor hydrothermal activity on a body other than Earth. Hydrothermal activity occurs when seawater infiltrates and reacts with a rocky core, emerging as a heated, mineral-laden liquid. This new finding opens the possibility for prebiotic or even biotic chemical mixtures to "slow-cook" inside Saturn's moon Enceladus, where the ocean meets hot rock.



There is a strong possibility that hot water rises from seafloor vents on Enceladus. This raises the potential for habitable environments beneath the ice crust of this small, active moon.

- Silica nanoparticles were captured by Cassini's cosmic dust analyzer. Analysis revealed these particles came from Enceladus' seafloor.

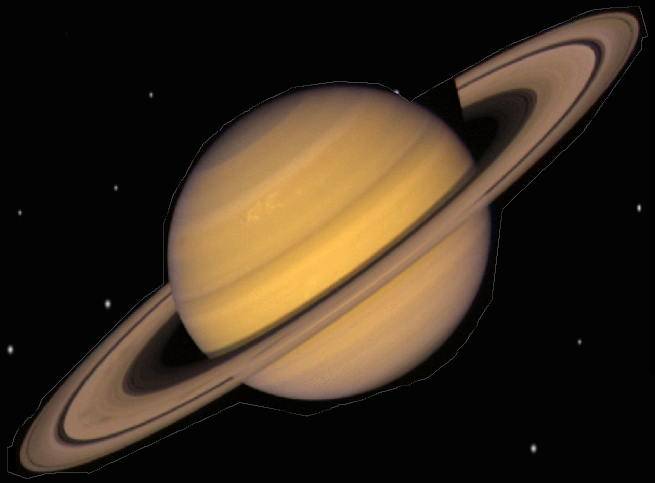
- Laboratory experiments indicate that these dust particles must have formed on the seafloor at temperatures above 90°C (194°F). This is a much hotter environment than scientists thought existed inside the icy moon, suggesting that seafloor hydrothermal activity is occurring.

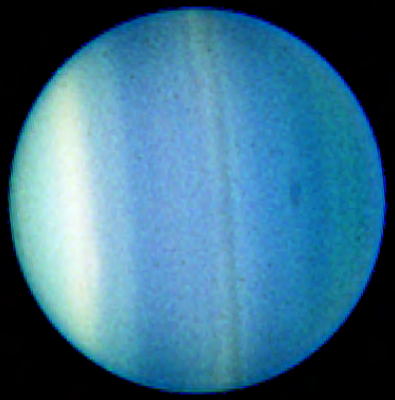
- Similar activity is observed around mid-Atlantic seafloor vents, where some extreme life forms reside.

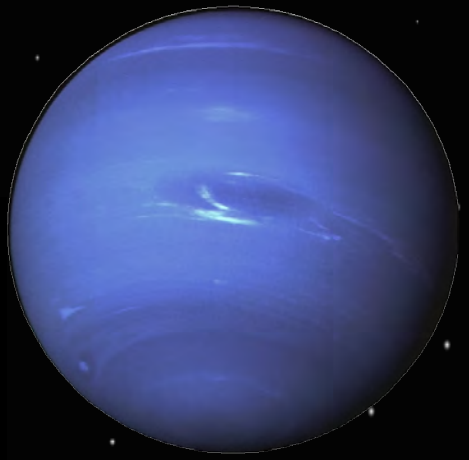
- This result shows that Enceladus' plume activity is an eruptive process that begins in its core and is not limited to the near-surface.

"Ongoing hydrothermal activities within Enceladus," Hsu *et al.*, *Nature,* March 12, 2015.

Outer Solar System Exploration







Worth the journey

BACKUP CHARTS

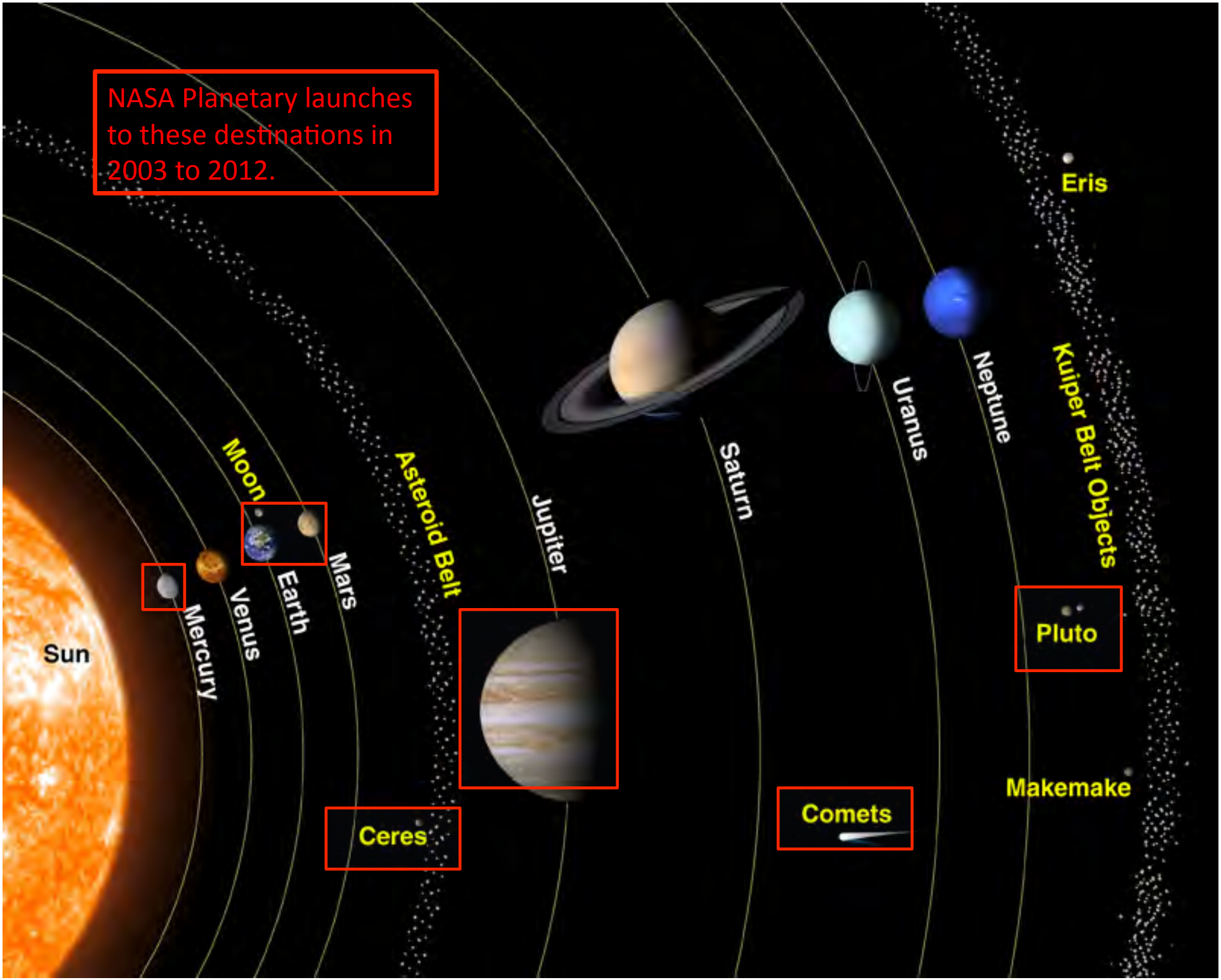
Why should we explore the Outer Solar System?

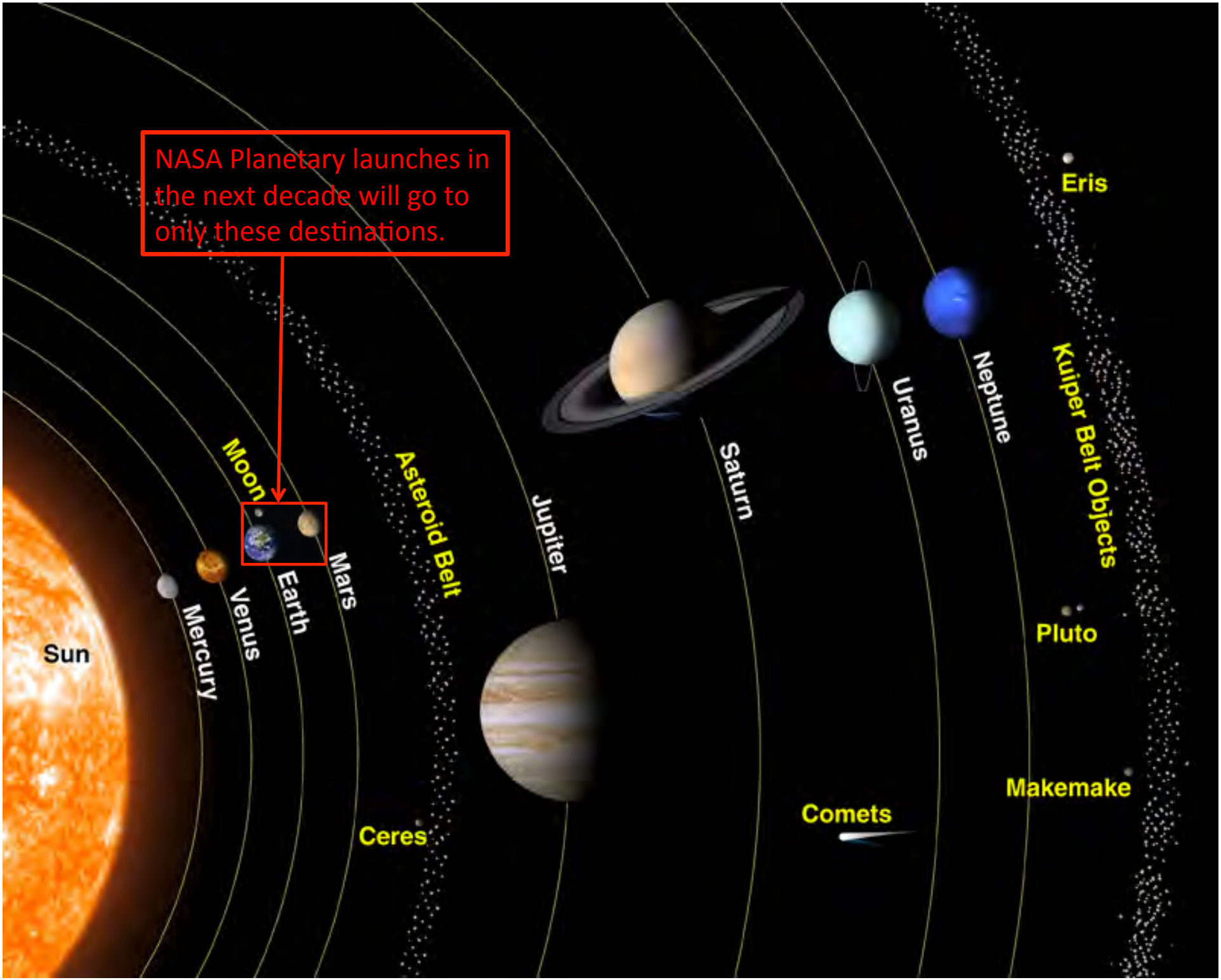
Why not just focus on Mars? (Mars is *a fascinating* planet, certainly worthy of exploration, but…)

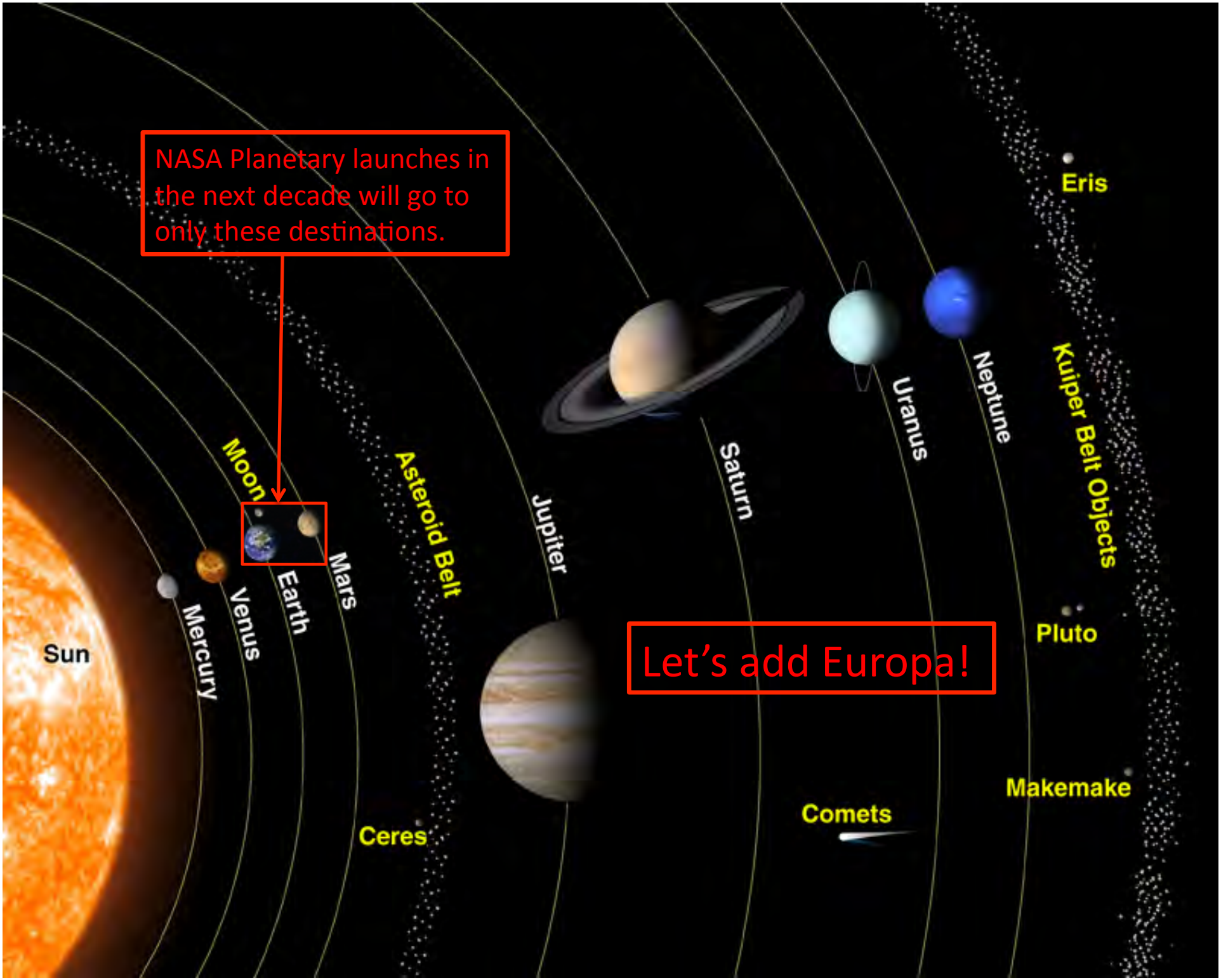
- Understanding *atmospheric circulation* – the giant outer planets have entirely different atmospheres than the terrestrial planets – understanding them means developing advanced fluid dynamics models (that have been applied for example to ocean currents)
- *Weather* more akin to earth: Earth is at the mercy of processes today that are taken to extremes on Saturn's moon Titan: a thick greenhouse atmosphere with violent rainstorms, desertification, and seas with coastline erosion and climate impact.
- *Atmospheric chemistry and astrobiology* - The reducing atmospheres in the outer solar system are home to a vigorous organic chemistry that does not occur in the inner solar system in the present day, providing an opportunity to study natural production of biological building blocks.
- *Magnetospheres* – the variety of the outer solar system tests our models and understanding of how our own magnetosphere is structured
- *Materials' behavior* in extreme pressures and temperatures not natural on earth – for example ice behaves like rock at outer solar system temperatures, but interior to many moons may be liquid
- *Exoplanets* – most of the new planets discovered around other stars are similar to Uranus and Neptune – we have a very limited understanding of our own ice giants

Treasures in the Outer Solar System

- *The outer solar system is target-rich*. We'd like to learn more about volcanoes on Io, storms on Titan, the rings around Uranus and whether Ariel is a frozen version of Enceladus. We'd like to study geysers on Triton, the plumes of Enceladus, and the magnetosphere of Neptune. And of course the highest priority of all is to learn more about Europa, a moon that could conceivably have life today in a subsurface ocean.
- We send our robotic emissaries to places too dangerous for humans – that doesn't make those places less worthy of exploration
- Destinations recommended in the Decadal Survey "Vision and Voyages" for the upcoming decade:
  - Europa, to learn more about the subsurface ocean and how to access it in the future
  - Uranus orbiter, to study an ice giant in our own solar system analogous to many exoplanets being discovered
  - Saturn probe, to study the layers under the cloudtops
  - Io volcano observer, to learn the secrets of the most volcanically active place in the solar system


NASA Planetary launches to these destinations in 2003 to 2012.
Sun
Mercury
Venus
Earth
Moon
Mars
Asteroid Belt
Ceres
Jupiter
Saturn
Uranus
Neptune
Kuiper Belt Objects
Eris
Pluto
Makemake
Comets


NASA Planetary launches in the next decade will go to only these destinations.
Sun
Mercury
Venus
Earth
Moon
Mars
Asteroid Belt
Ceres
Jupiter
Saturn
Uranus
Neptune
Kuiper Belt Objects
Eris
Pluto
Makemake
Comets


NASA Planetary launches in the next decade will go to only these destinations.
Let's add Europa!
Sun
Mercury
Venus
Earth
Moon
Mars
Asteroid Belt
Ceres
Jupiter
Saturn
Uranus
Neptune
Kuiper Belt Objects
Eris
Pluto
Makemake
Comets